Planned Physics Measurements with SoLID at 12-GeV Jefferson Lab

- Introduction
- Results from JLab Experiment E06-010
- TMDs @ SoLID
- Summary

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IIFF2013

TUNL

QCD ⟷ *Nucleon Structure*

- **Strong interaction, running coupling ~1**

  -- QCD: the theory of strong interaction

  -- asymptotic freedom (2004 Nobel)

  perturbation calculation works at high energy

  -- interaction significant at intermediate energy

  quark-gluon correlations

  -- confinement

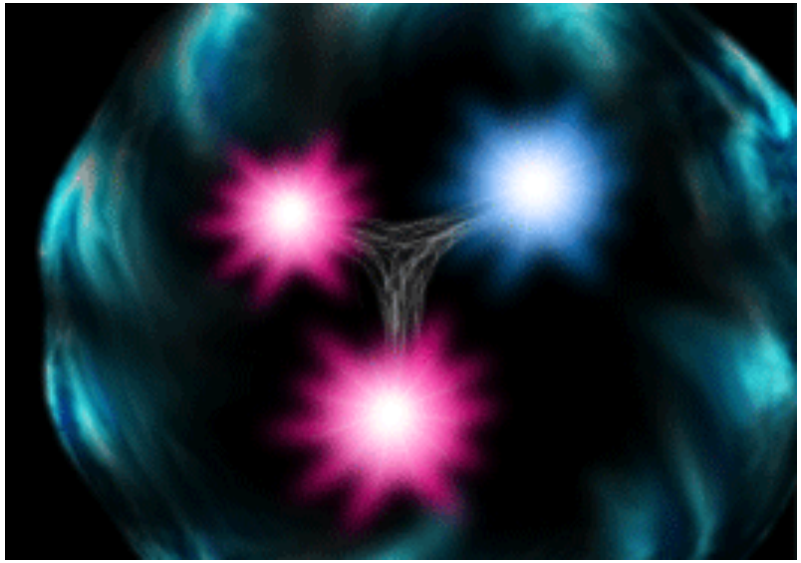
  interaction strong at low energy

  coherent hadron

  -- Chiral symmetry

  -- theoretical tools:

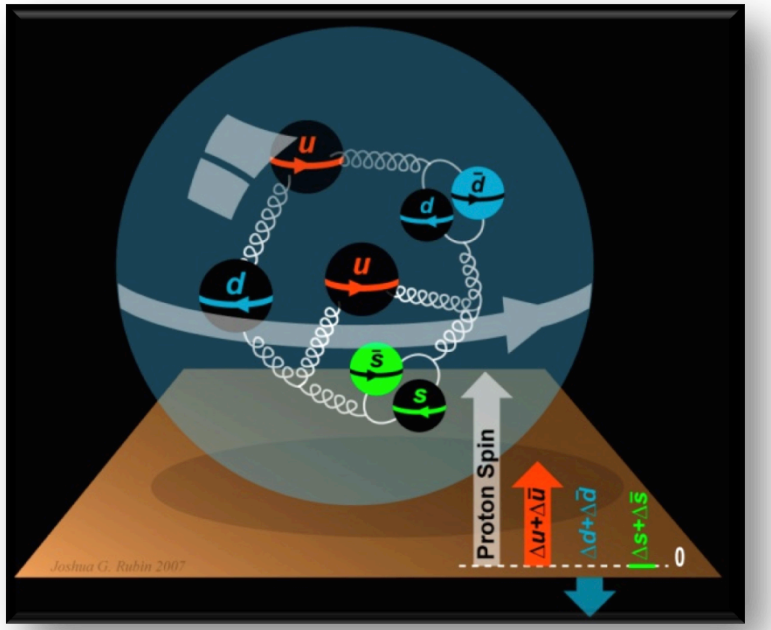
  pQCD, OPE, Lattice QCD, ChPT



- ***Charge and magnetism (current) distribution*** E
- ***Spin distribution***
- ***Quark momentum and flavor distribution***
- ***Polarizabilities***
- ***Strangeness content***
- ***Three-dimensional structure***
- ***……***

Spin as an important knob

The Incomplete Nucleon: Spin Puzzle



$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma(\mu) + L_q(\mu) + J_g(\mu)$$

[X. Ji, 1997]

Jaffe-Manohar 1990

Chen *et al.* 2008

Wakamatsu 2009,2010

- DIS $\rightarrow \Delta\Sigma \cong 0.30$
- RHIC + DIS $\rightarrow \Delta g$ not small
- $\rightarrow L_q$

Orbital angular momentum of quarks and gluo is important

Understanding of spin-orbit correlations (atomic hydrogen, topological insulator…..)

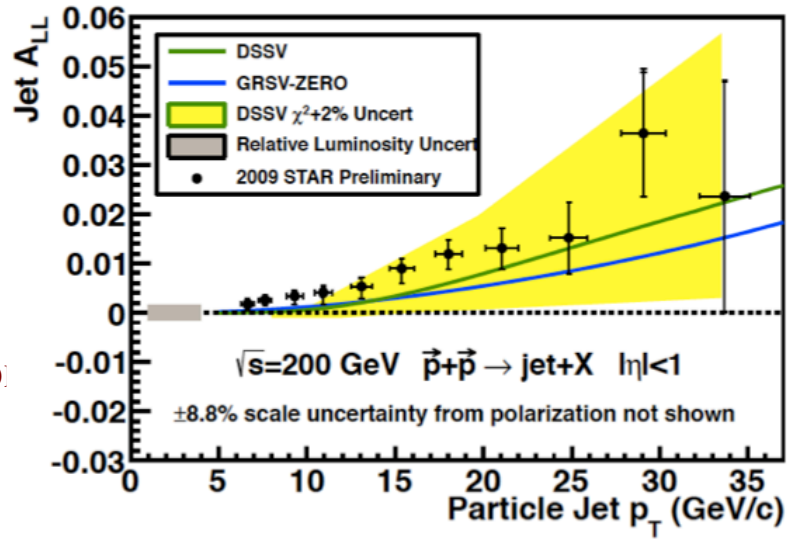
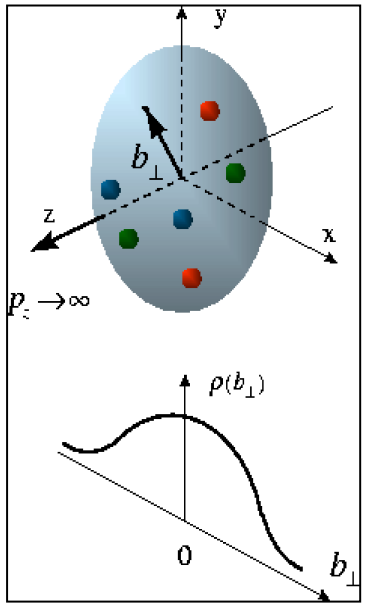


Figure credit to STAR Collaboration

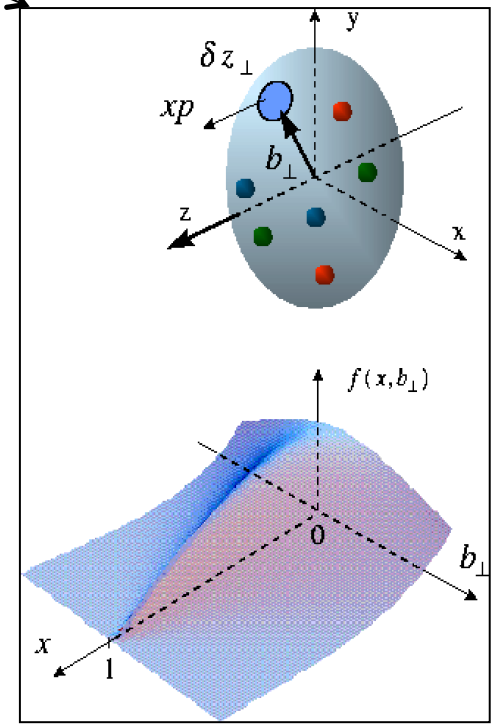
How to access OAM?

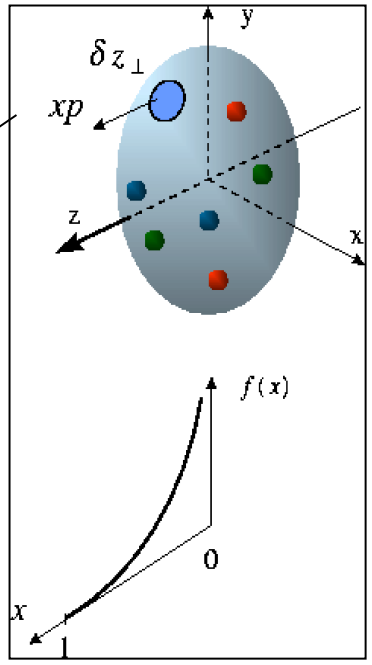
Generalized Parton Distributions (GPDs)

D. Mueller, X. Ji, A. Radyushkin, A. Belitsky, …



GPDs connect the charge and parton distribution



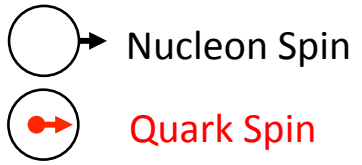


The size and structure of proton.
Proton form factors, transverse charge and current distributions
Nobel prize 1961- R. Hofstadter

Internal constituents of the nucleon
Quark longitudinal momentum and helicity distributions
Nobel prize 1990 - J. Friedman, H. Kendall, R. Taylor

Extend longitudinal quark momentum & helicity distributions to transverse momentum distributions - TMDs

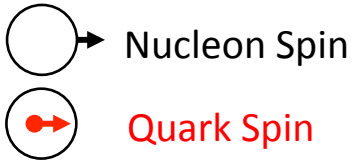
Leading-Twist TMD PDFs



Nucleon Polarization	Quark polarization: Unpolarized (U)	Quark polarization: Longitudinally Polarized (L)	Quark polarization: Transversely Polarized (T)
U	f_1 =		$h_1^\perp$ = − **Boer-Mulders**
L		g_1 = − **Helicity**	$h_{1L}^\perp$ = − **Long-Transversity**
T	$f_{1T}^\perp$ = − **Sivers**	g_{1T} = − **Trans-Helicity**	h_1 = − **Transversity**; $h_{1T}^\perp$ = − **Pretzelosity**

Probed with transversely polarized target
HERMES, COMPASS, JLab E06-010

Leading-Twist TMD PDFs



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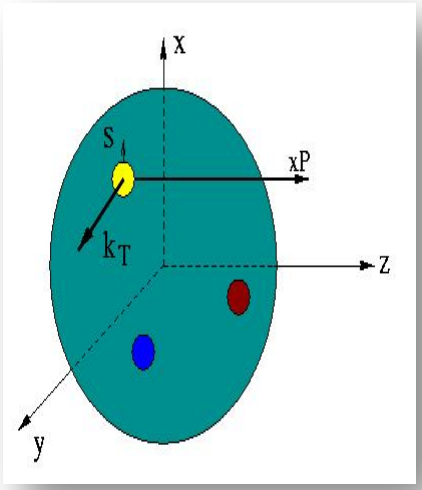
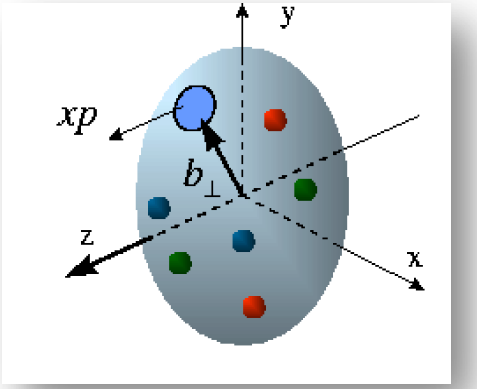
Unified View of Nucleon Structure

$W_p^u(x,k_T,\boldsymbol{r}_T)$ Wigner distributions

5D Dist.





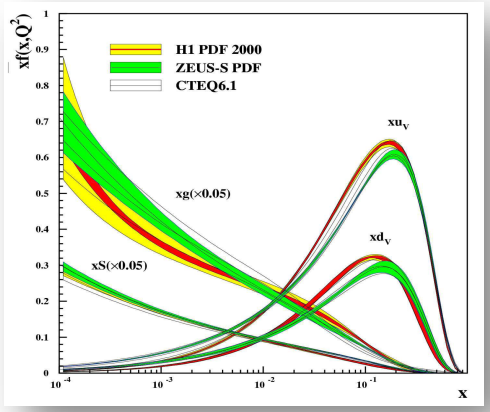
$d^3\boldsymbol{r}$ $d^2k_T\,dr_z$

TMD PDFs $f_1^u(x,k_T)$, .. $h_1^u(x,k_T)$

GPDs/IPDs

3D imaging

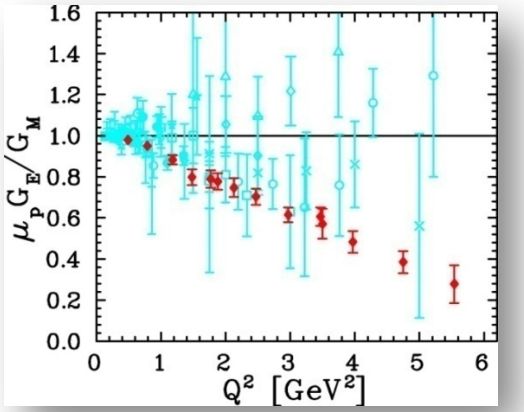
d^2k_T d^2r_T dx & Fourier Transformation



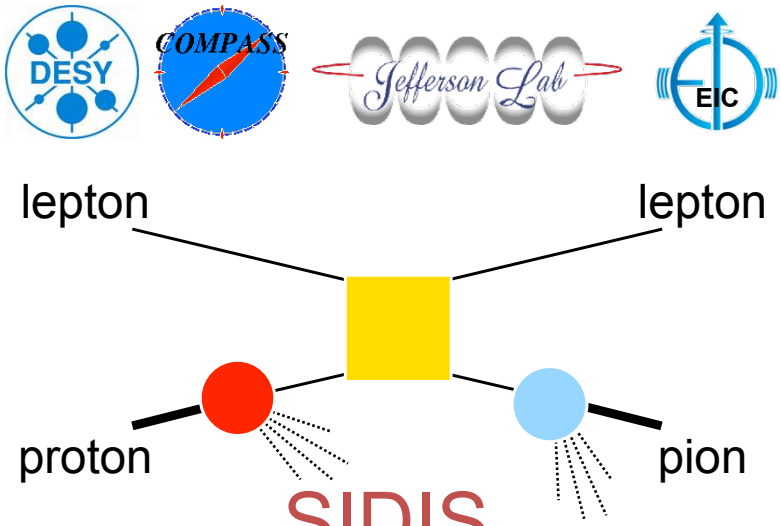
PDFs $f_1^u(x)$, .. $h_1^u(x)$

1D

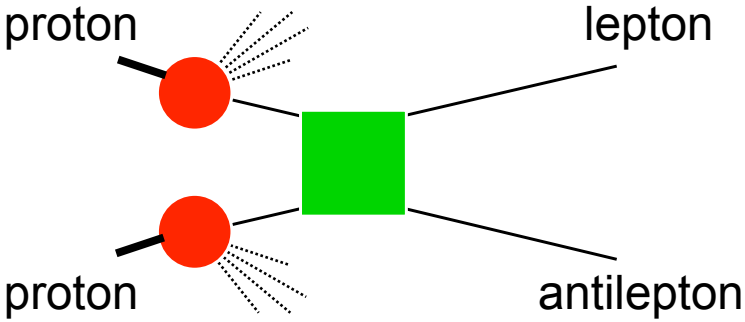
Form Factors $G_E(Q^2)$, $G_M(Q^2)$



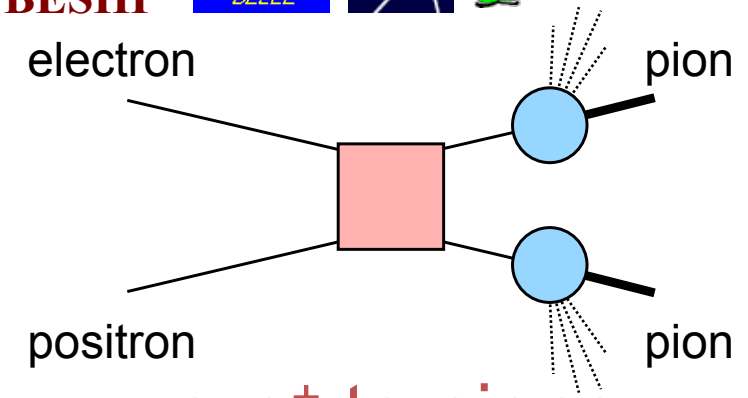
Access TMDs through Hard Processes



SIDIS



Drell-Yan



e^-e^+ to pions

Partonic scattering amplitude

Fragmentation amplitude

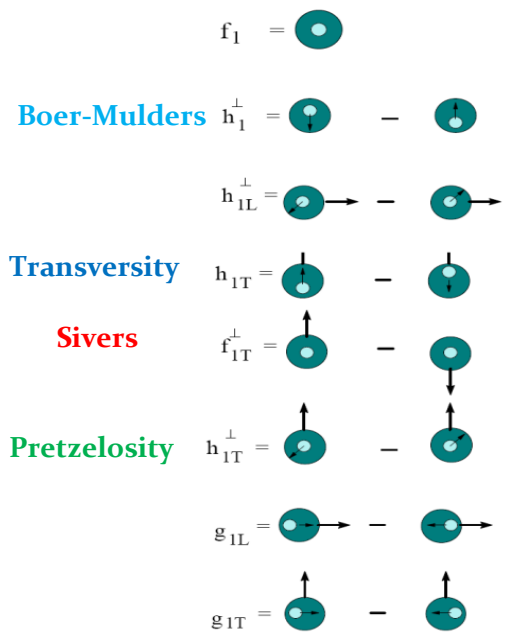
Distribution amplitude

$$f_{1T}^{\perp q}(\text{SIDIS}) = -f_{1T}^{\perp q}(\text{DY})$$

$$h_1^{\perp}(\text{SIDIS}) = -h_1^{\perp}(\text{DY})$$

Access Parton Distributions through Semi-Inclusive DIS

$$\frac{d\sigma}{dx dy d\phi_S dz d\phi_h dP_{h\perp}^2} = \frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\cdot$$



$$\{F_{UU,T} + \ldots$$
$$+ \varepsilon \cos(2\phi_h)\cdot F_{UU}^{\cos(2\phi_h)} + \ldots$$

Unpolarized

$$+ S_L[\varepsilon \sin(2\phi_h)\cdot F_{UL}^{\sin(2\phi_h)} + \ldots]$$
$$+ S_T[\varepsilon \sin(\phi_h + \phi_S)\cdot F_{UT}^{\sin(\phi_h+\phi_S)}$$
$$+ \sin(\phi_h - \phi_S)\cdot (F_{UL}^{\sin(\phi_h-\phi_S)} + \ldots)$$
$$+ \varepsilon \sin(3\phi_h - \phi_S)\cdot F_{UT}^{\sin(3\phi_h-\phi_S)} + \ldots]$$

Polarized Target

$$+ S_L\lambda_e[\sqrt{1-\varepsilon^2}\cdot F_{LL} + \ldots]$$
$$+ S_T\lambda_e[\sqrt{1-\varepsilon^2}\cos(\phi_h - \phi_S)\cdot F_{LT}^{\cos(\phi_h-\phi_S)} + \ldots]\}$$

Polarized Beam and Target

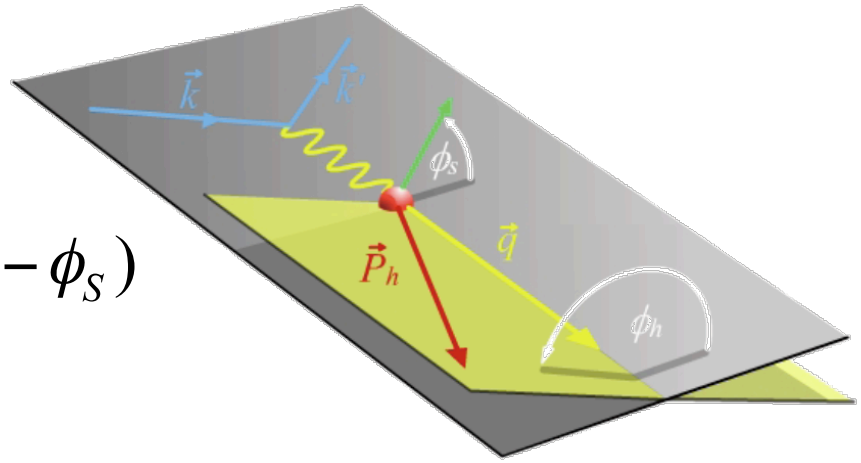
S_L, S_T: Target Polarization; λ_e: Beam Polarization

Separation of Collins, Sivers and pretzelocity effects through angular dependence

$$A_{UT}(\varphi_h^l, \varphi_S^l) = \frac{1}{P}\frac{N^{\uparrow} - N^{\downarrow}}{N^{\uparrow} + N^{\downarrow}}$$

$$= A_{UT}^{Collins} \sin(\phi_h + \phi_S) + A_{UT}^{Sivers} \sin(\phi_h - \phi_S)$$

$$+ A_{UT}^{Pretzelosity} \sin(3\phi_h - \phi_S)$$



$$A_{UT}^{Collins} \propto \left\langle \sin(\phi_h + \phi_S) \right\rangle_{UT} \propto h_1 \otimes H_1^{\perp}$$

Collins frag. Func. from e^+e^- collisions

$$A_{UT}^{Sivers} \propto \left\langle \sin(\phi_h - \phi_S) \right\rangle_{UT} \propto f_{1T}^{\perp} \otimes D_1$$

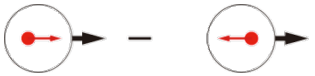
$$A_{UT}^{Pretzelosity} \propto \left\langle \sin(3\phi_h - \phi_S) \right\rangle_{UT} \propto h_{1T}^{\perp} \otimes H_1^{\perp}$$

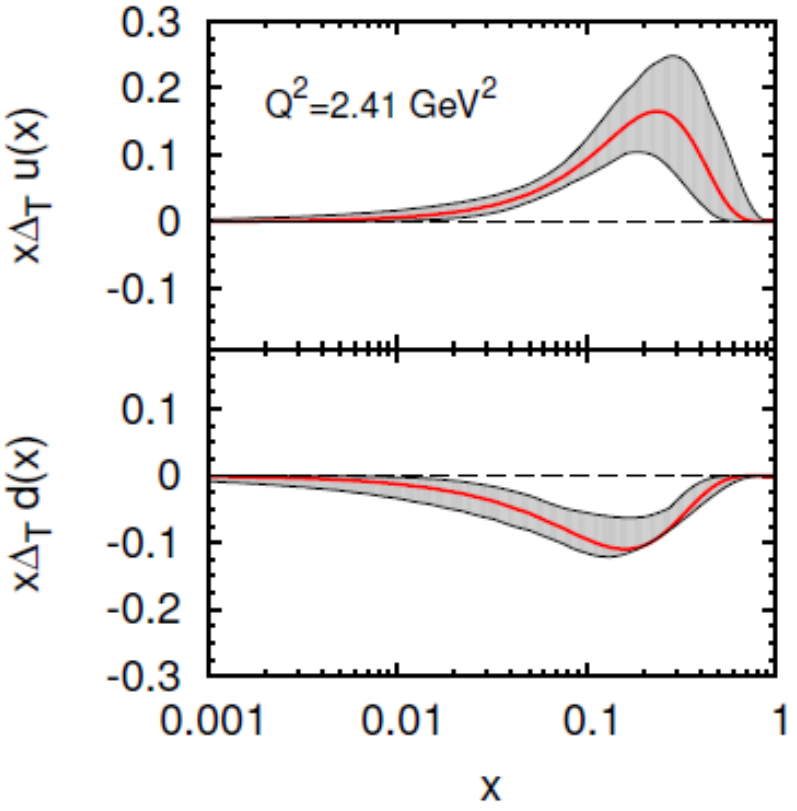
SIDIS SSAs depend on 4-D variables (x, Q^2, z and P_T)

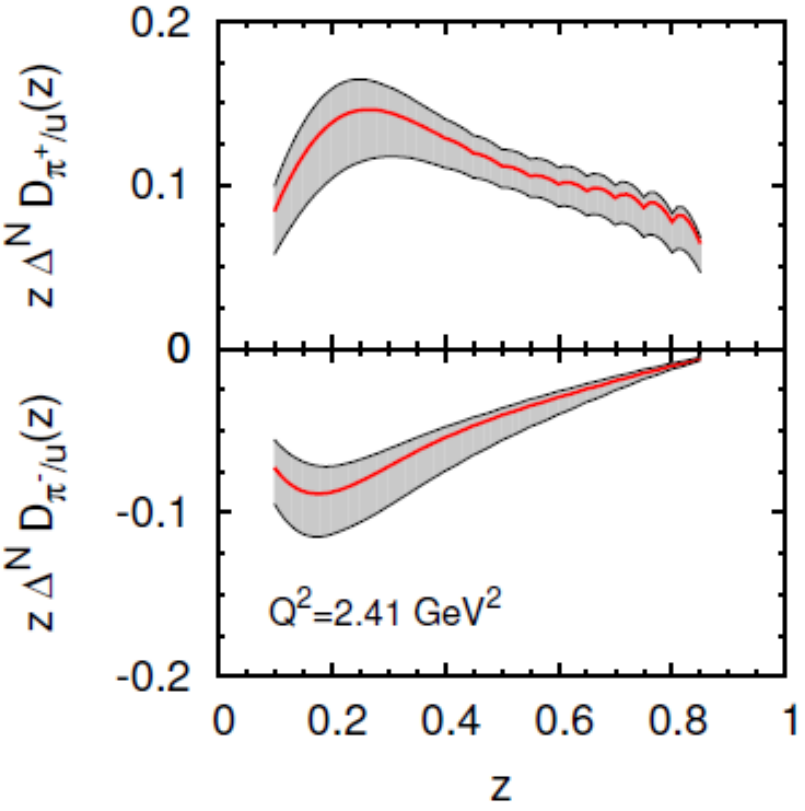
Large angular coverage and precision measurement of asymmetries in 4-D phase space is essential.

Transversity

h_{1T} = 

- The third PDFs in addition to f_1  and g_{1L} 





$\Delta_T = h_{1T}$

A global fit to the HERMES, COMPASS and BELLE e+e- data
Anselmino et al., arXiv:1303.3822

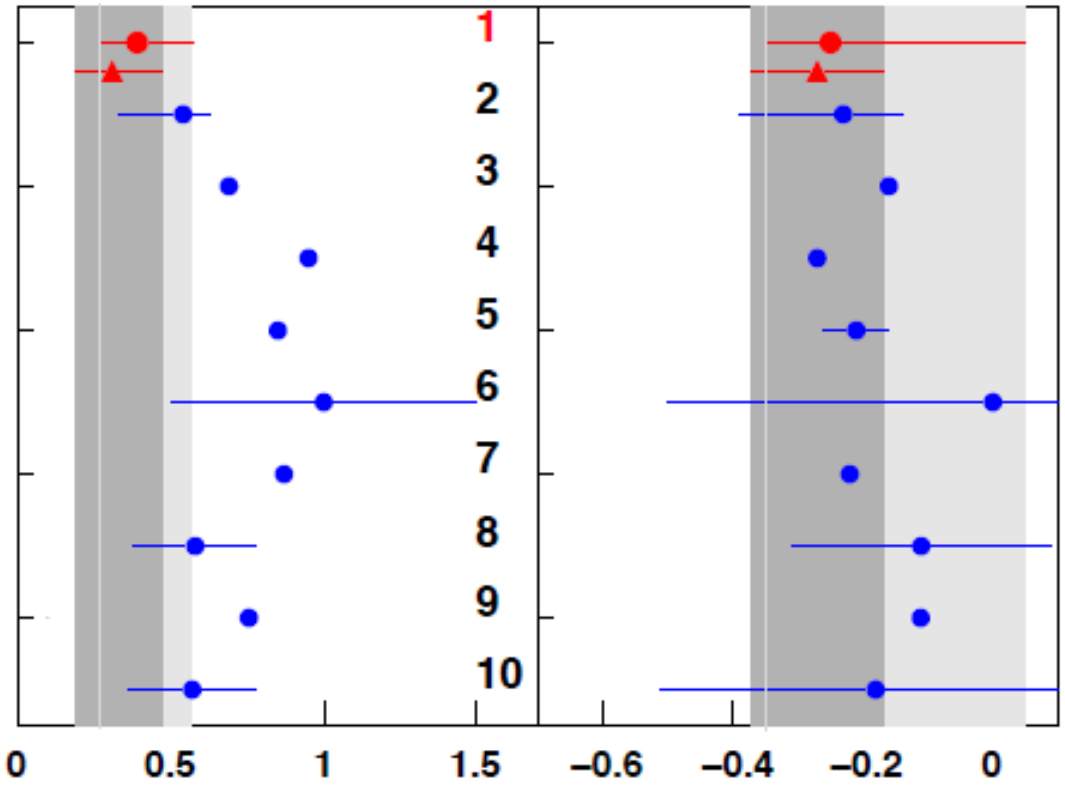
Transversity

h_{1T} =  –

- Lowest moment gives tensor charge $\delta q^a = \int_0^1 (h_{1T}^a(x) - h_{1T}^{\bar{a}}(x))dx$
  - Fundamental property, benchmark test of Lattice QCD

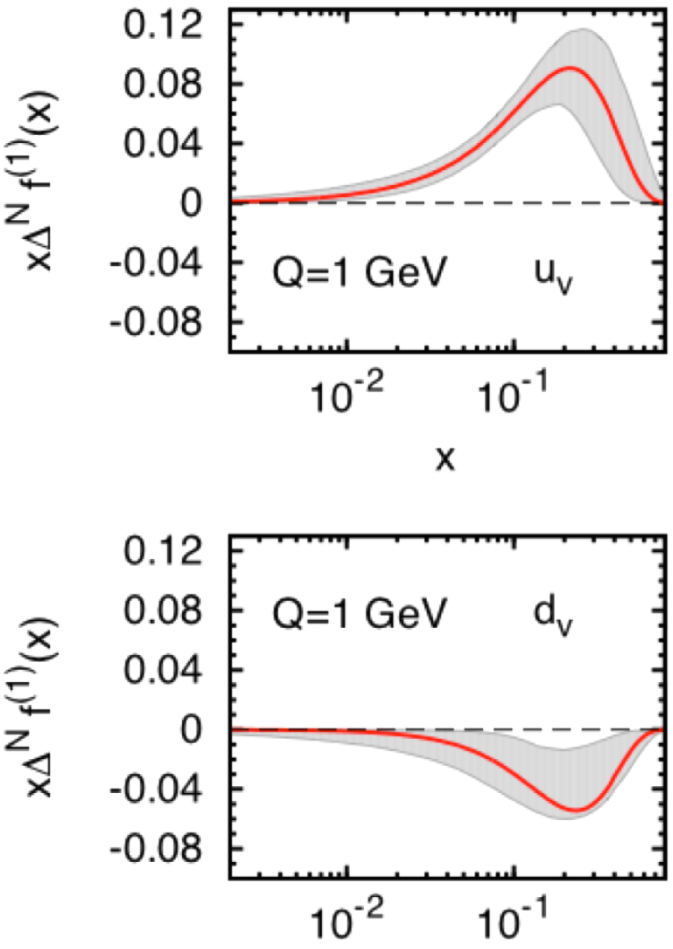
$\bullet\ \delta u = 0.39^{+0.18}_{-0.12}$ $\bullet\ \delta d = -0.25^{+0.30}_{-0.10}$

$\blacktriangle\ \delta u = 0.31^{+0.16}_{-0.12}$ $\blacktriangle\ \delta d = -0.27^{+0.10}_{-0.10}$

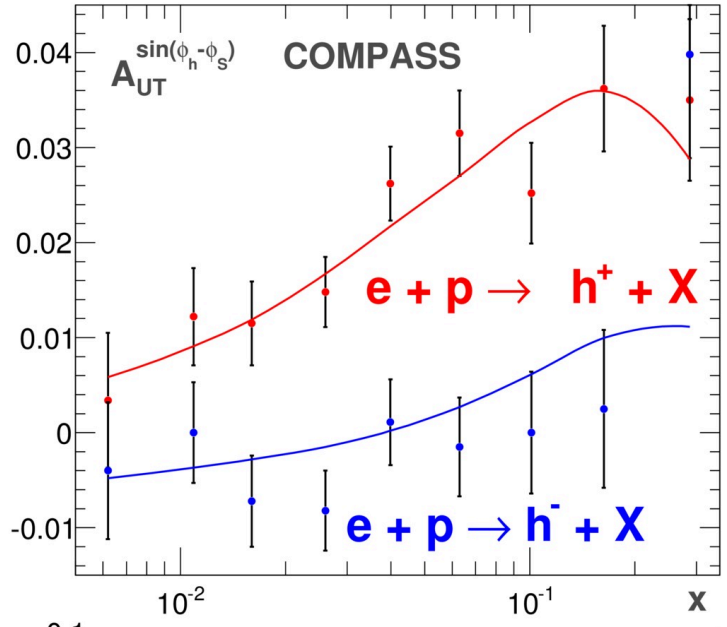


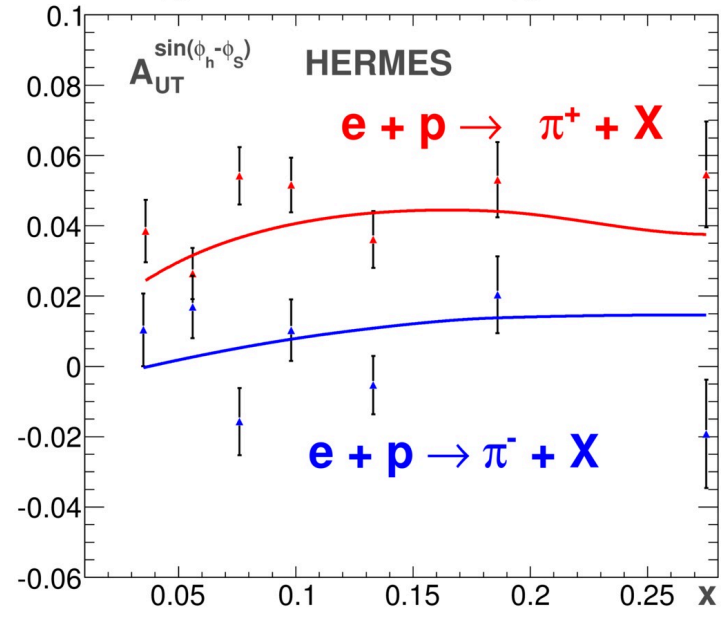
Anselmino et al., arXiv:1303.3822

SIVERS FUNCTION - TMD



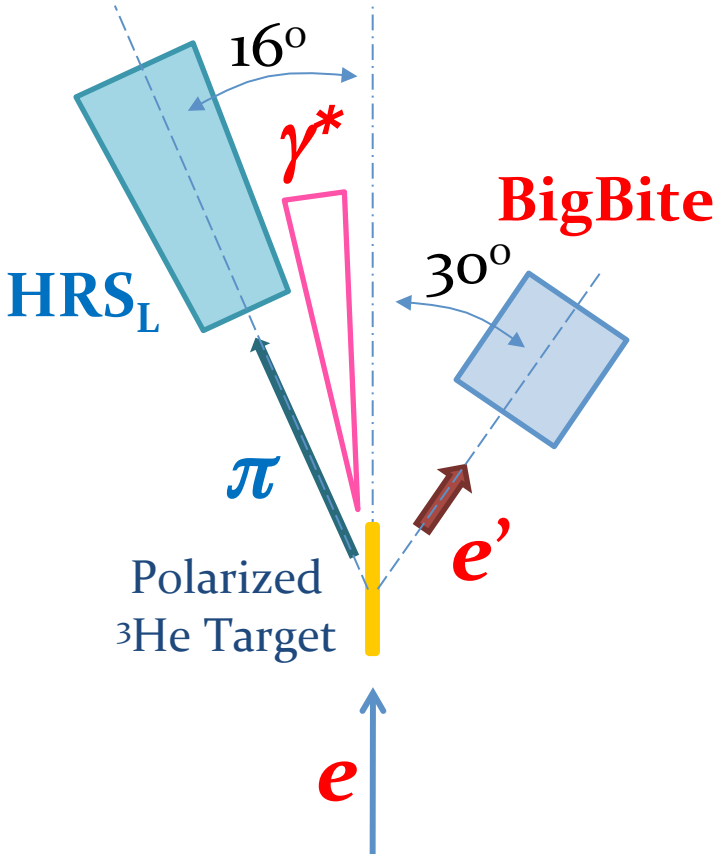
Extraction based on HERMES, COMPASS data arXiv:1204.1239 including TMD evolution





Energy evolution in SIDIS and D-Y
Sun and Yuan, arXiv:1304.5037

E06-010: neutron $A_{(U/L)T}(\pi^+K^+, \pi^-K^-)$

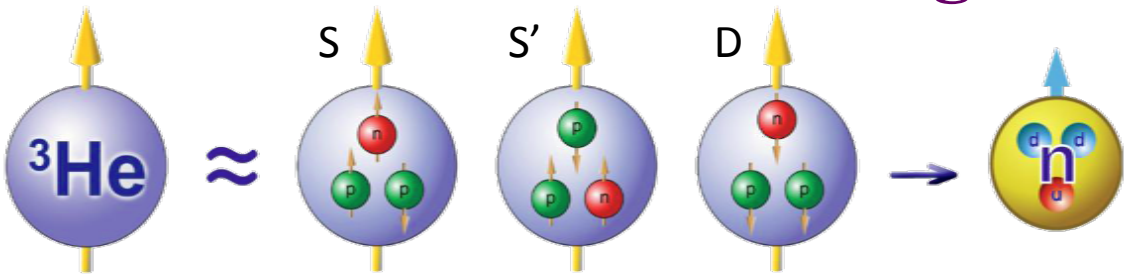


- ***First*** **neutron** data in SIDIS SSA&DSA
  - Similar Q^2 as HERMES experiment
- Disentangle Collins/Sivers effects

- Electron beam: ***E*** = 5.9 GeV
- High luminosity L ~ 10^{36} $cm^{-2}s^{-1}$
  - 40 cm transversely polarized ^{3}He target
  - Average beam current 12 uA (max: 15 uA as in proposal)

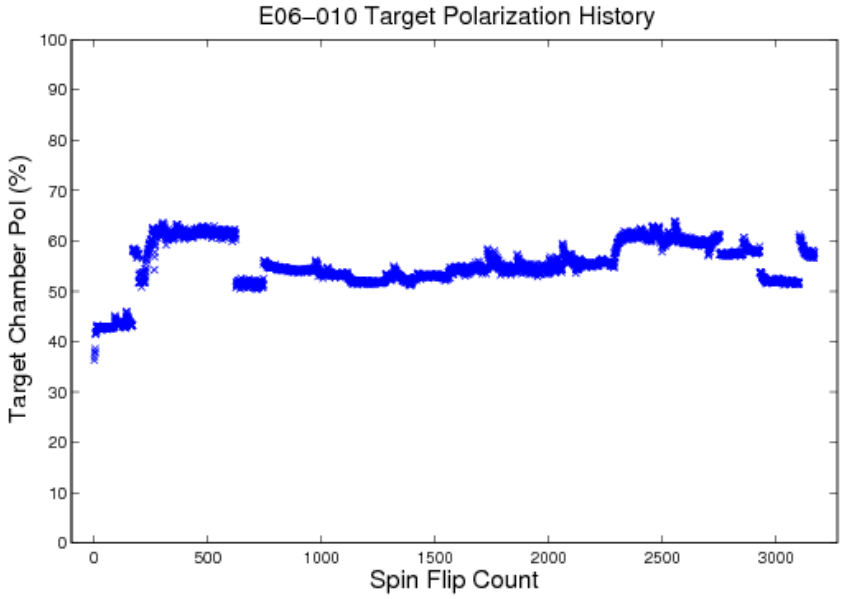
- BigBite at 30° as **electron** arm:
  P_e = 0.6 ~ 2.5 GeV/c
- HRSL at 16° as **hadron** arm: P_h
  = 2.35 GeV/c

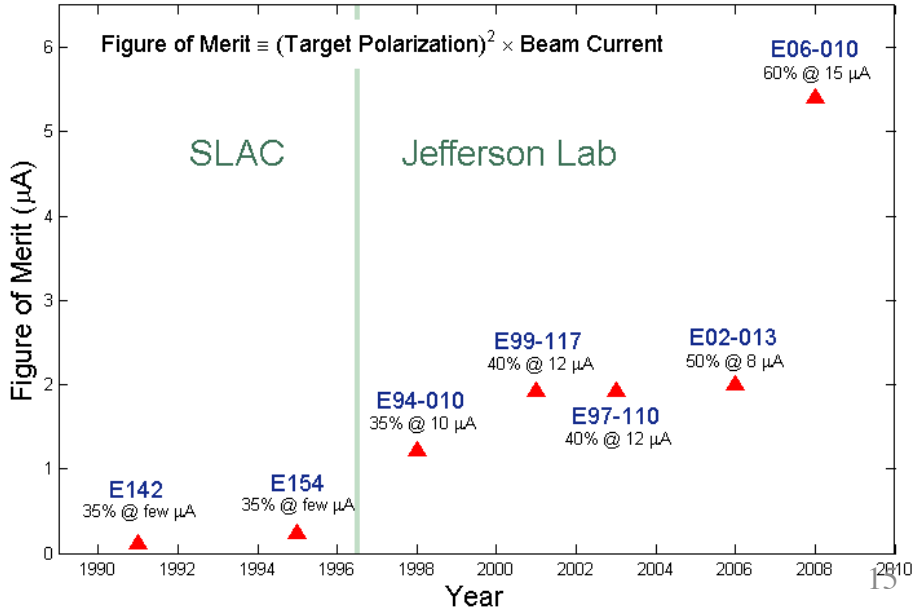
^{3}He Target



Effective Polarized Neutron Target!

- Polarized ^{3}He ran reliably throughout the experiment, and the following three experiments.
- Reached **55%-60%** polarization with 15 μA beam and 20 minute spin flip! **A NEW RECORD!**

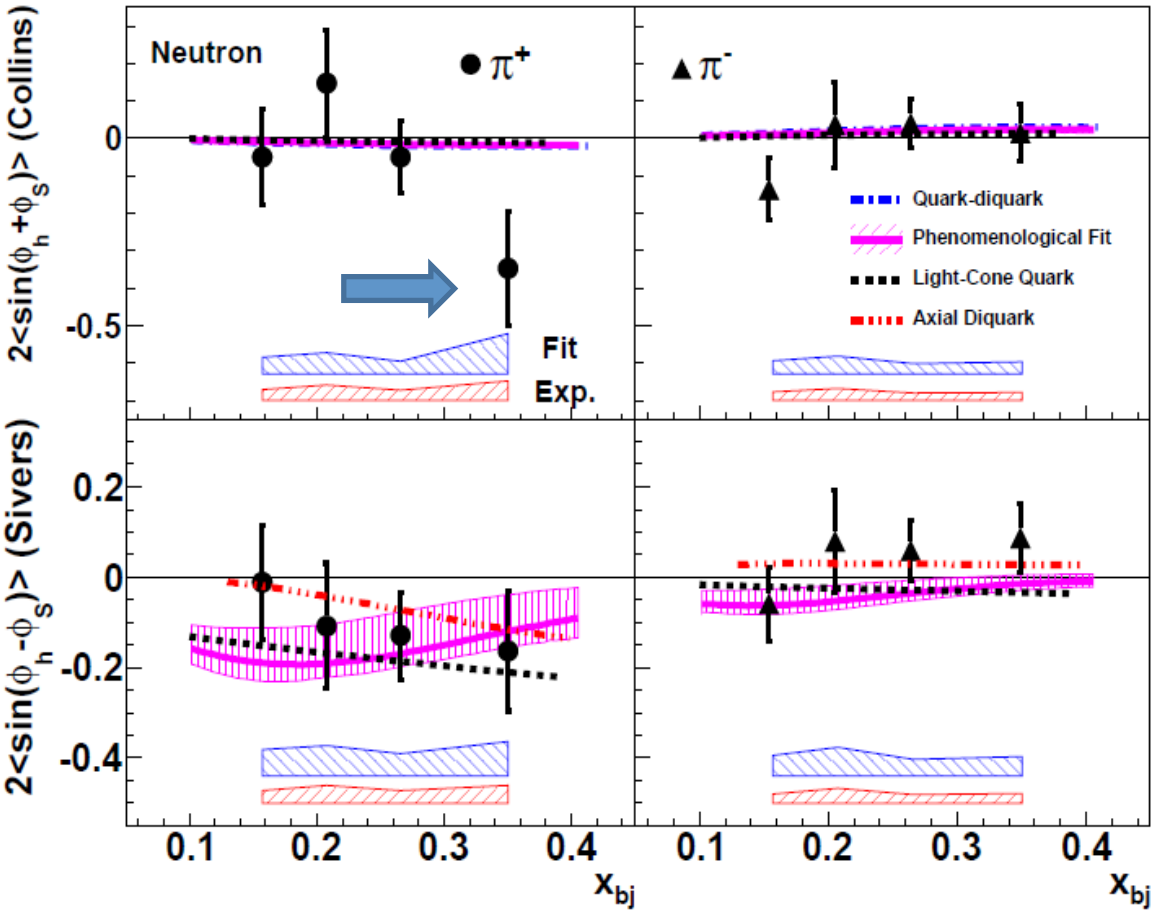




Results on Neutron

- Sizable Collins π^+ asymmetries at x=0.34?
  - Sign of violation of Soffer's inequality?
  - **Data are limited by stat. Needs more precise data!**

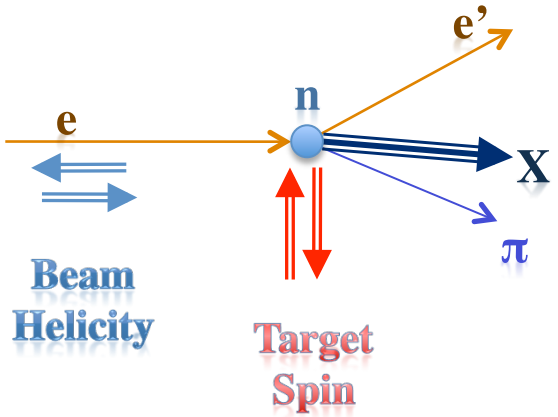
- Negative Sivers π^+ Asymmetry
  - Consistent with HERMES/ COMPASS
  - **Independent**
  - **demonstration of negative d quark Sivers function.**

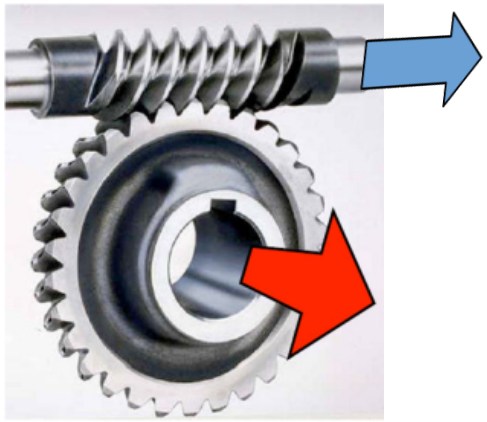


Model (fitting) uncertainties shown in blue band.
Experimental systematic uncertainties: red band
X. Qian *et al*, Phys. Rev. Lett. 107, 072003 (2011)

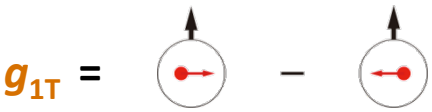
Double Spin Asymmetry: g_{1T}

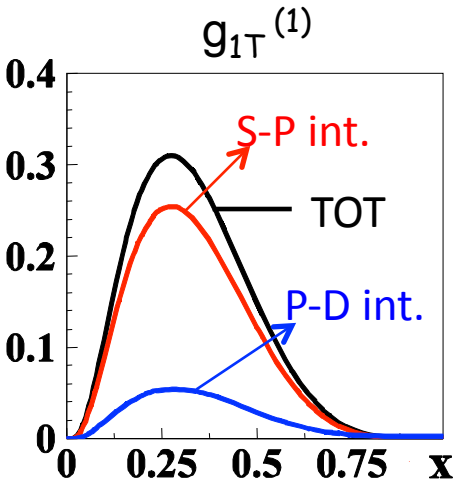
- $A_{\mathrm{LT}}^{\cos(\phi_h - \phi_s)} \propto g_{1T}^{q} \otimes D_{1q}^{h}$
  - Leading twist TMD PDFs
  - T-even, Chiral-even
- Dominated by real part of interference between L=0 (S) and L=1 (P) states
  - Imaginary part -> Sivers effect
- First TMDs in Pioneer Lattice calculation
  - arXiv:0908.1283 [hep-lat], Europhys.Lett.88:61001,2009
  - arXiv:1011.1213 [hep-lat] , Phys.Rev.D83:094507,2011





Worm Gear





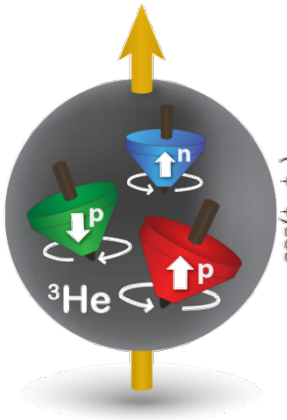
Light-Cone CQM by B. Pasquini
B.P., Cazzaniga, Boffi, PRD78, 2008

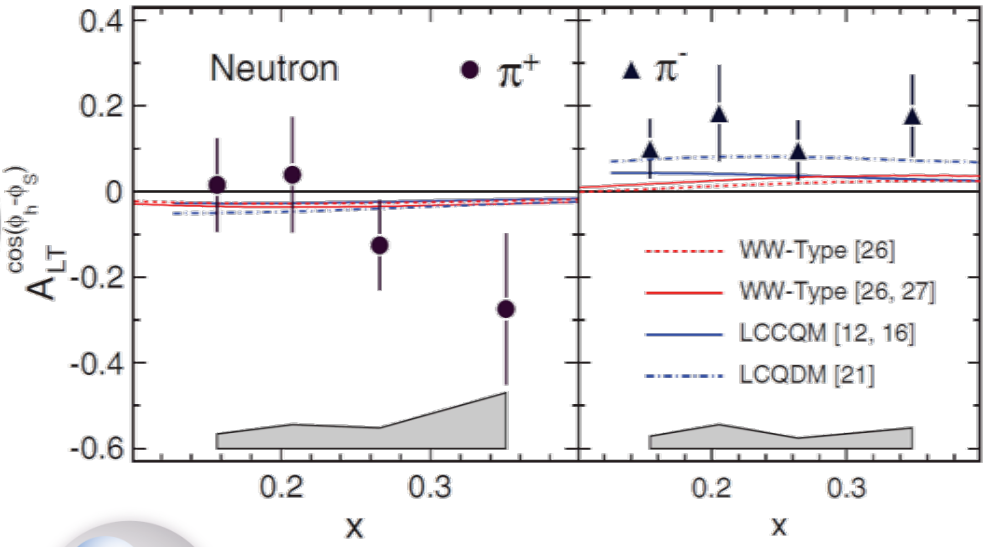
New Observable Reveals Interesting Behaviors of Quarks

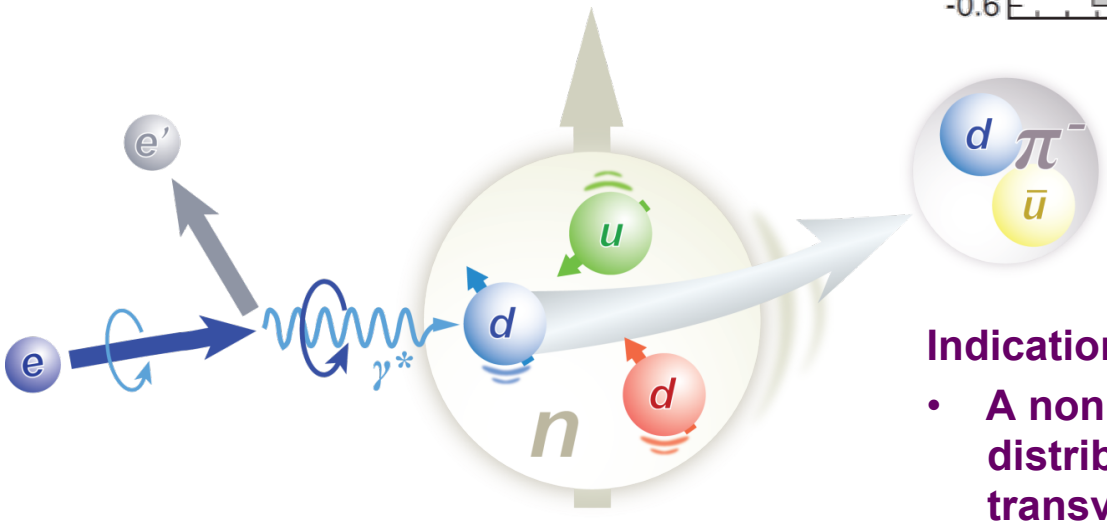
$$A_{\mathrm{LT}}^{\cos(\phi_h - \phi_s)} \propto g_{1T}^{q} \otimes D_{1q}^{h}$$

Huang, *et. al.* PRL. 108, 052001 (2012)

Target:
polarized ^{3}He => polarized neutron







First measurement of A_{LT}
beam-target double-spin asymmetry

Indications:

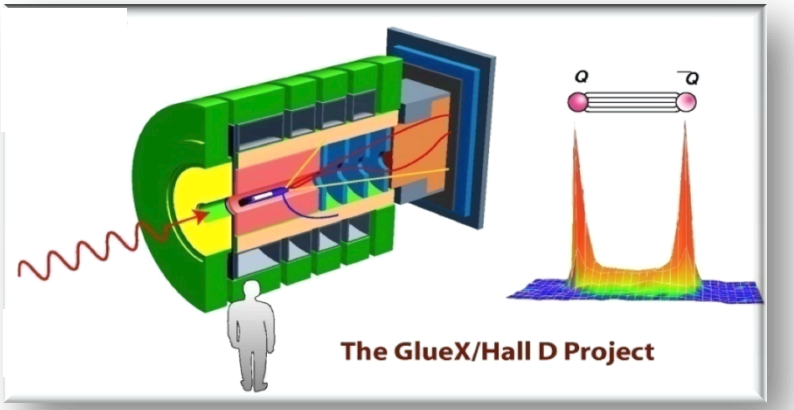
- **A non-vanishing quark "transversal helicity" distribution, reveals alignment of quark spin transverse to neutron spin direction**
- **Quark orbital motions**

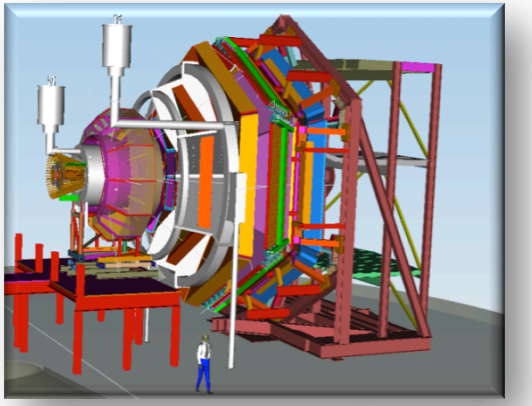
Hermes showed preliminary results from the proton

J. Huang et al., PRL108, 052001 (2012)

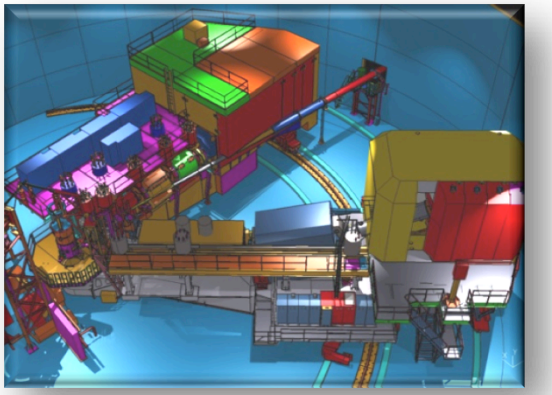
12 GeV Scientific Capabilities

Hall D – exploring origin of confinement by studying exotic mesons

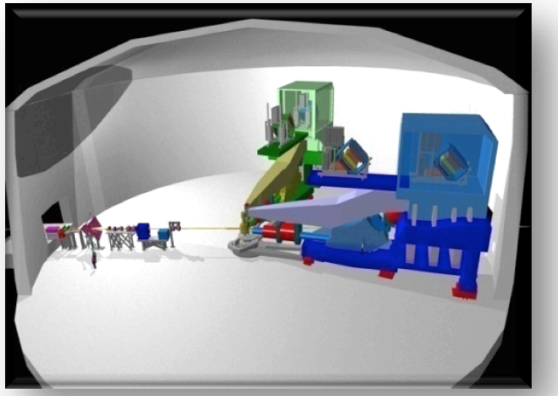




Hall B – understanding nucleon structure via generalized parton distributions and TMDs



Hall C – precision determination of valence quark properties in nucleons and nuclei

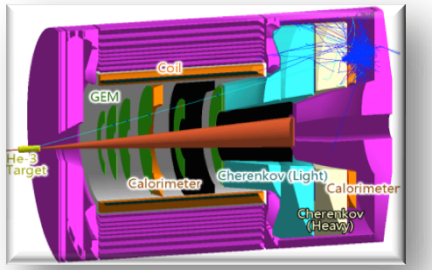


Hall A – short range correlations, form factors, hyper-nuclear physics, future new experiments (e.g., PV, MOLLER and SoLID)

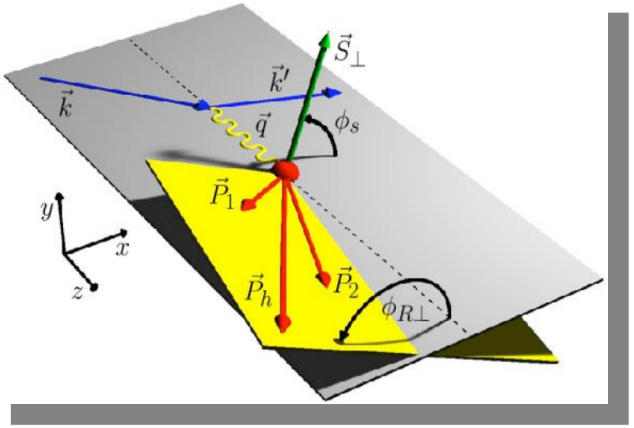
Multi-Halls SIDIS Program

Hall A/SBS
High x - Q^2, 2-3D

Hall A/SoLID
High Lumi and acceptance – 4D



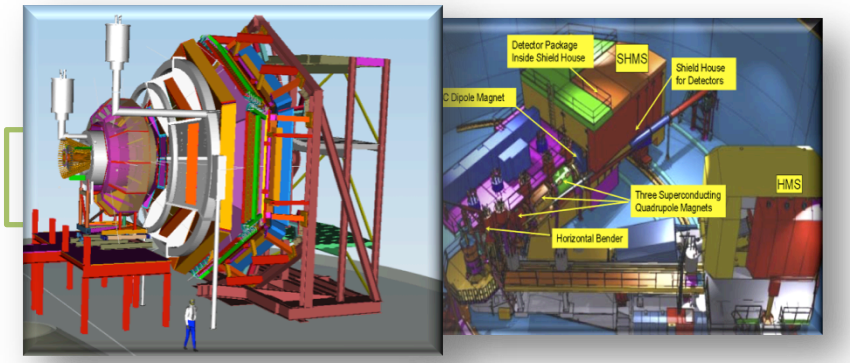
^{3}He, NH_3



N \ q	U	L	T
U	f_1		$h_1^\perp$
L		g_1	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1 $h_{1T}^\perp$

Hall B/CLAS12
General survey, medium luminosity

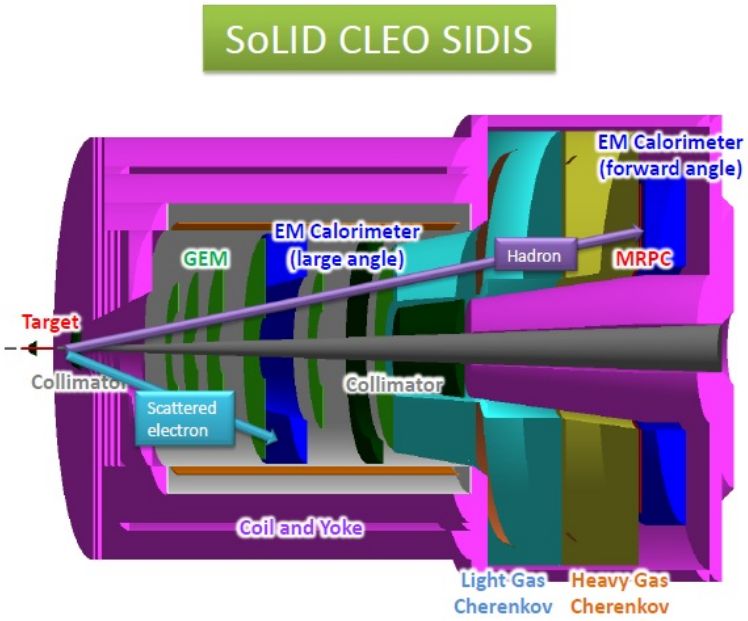
Hall C/SHMS
L-T studies, precise π^+/π^- ratios



H_2/D_2, NH_3/ND_3, HD

H_2
D_2

SoLID-Spin: SIDIS on ^{3}He/Proton @ 11 GeV

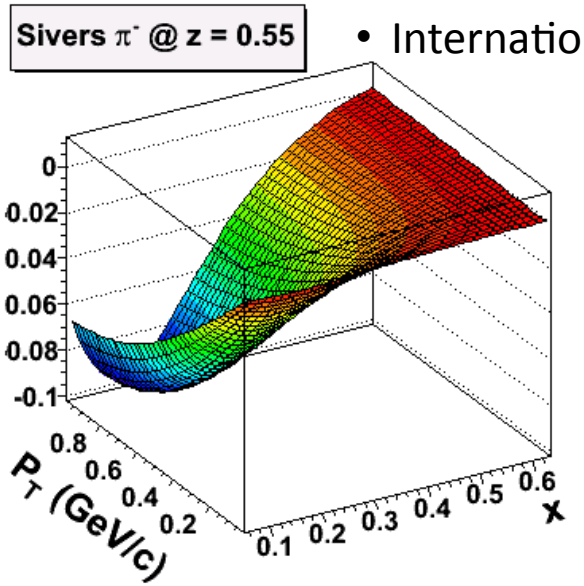


E12-10-006: Single Spin Asymmetry on Transverse ^{3}He @ 90 days, **rating A**

E12-11-007: Single and Double Spin Asymmetry on ^{3}He @ 35 days, **rating A**

E12-11-108: Single and Double Spin Asymmetries on Transverse Proton @120 days, **rating A**

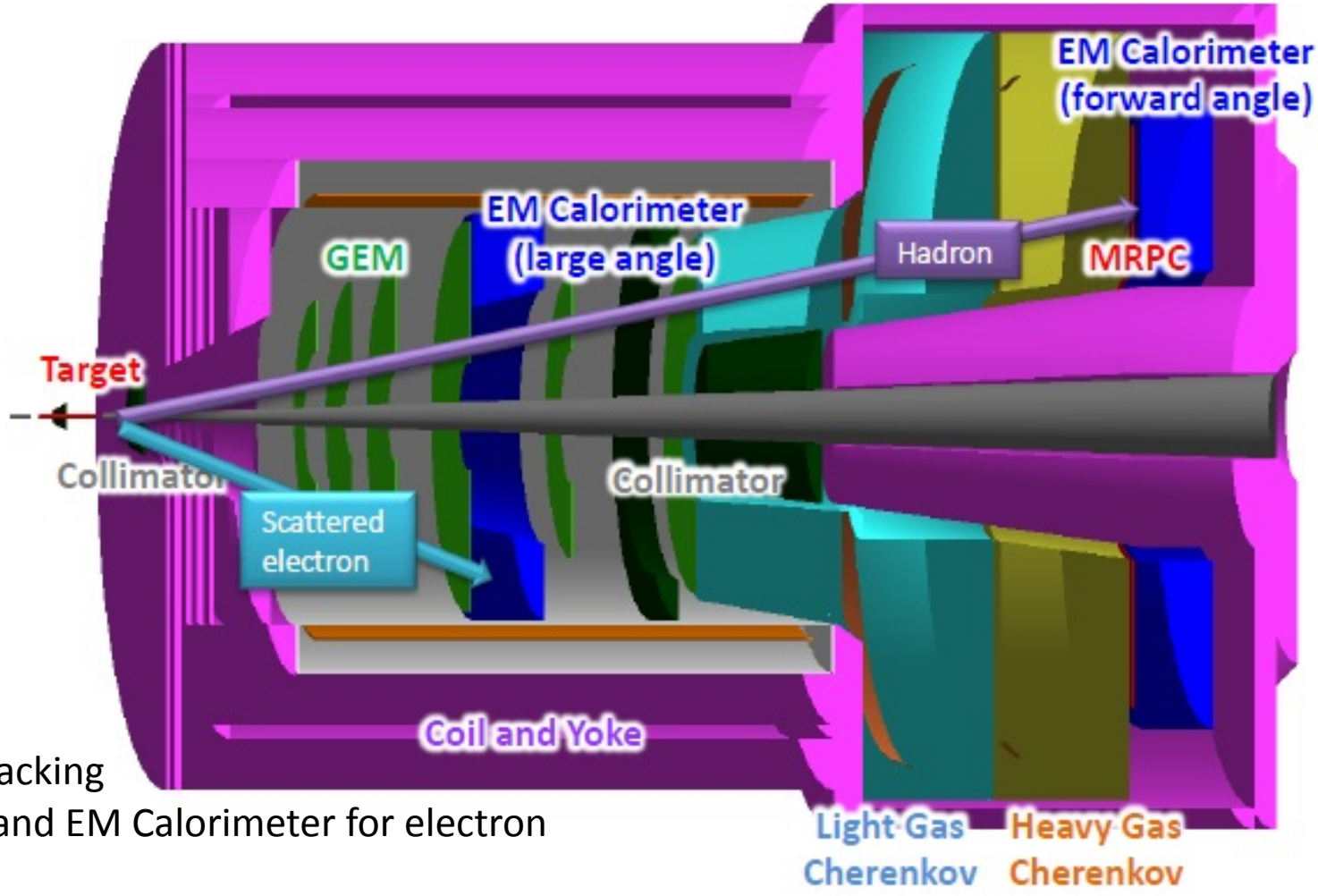
one PVDIS "A rated", one J/Psi "A- rated"



- International collaboration: eight countries and 50+ institutions

Key of SoLID-Spin program:
Large Acceptance
+ High Luminosity
→ **4-D** mapping of asymmetries
→ Tensor charge, TMDs …
→Lattice QCD, QCD Dynamics, Models.

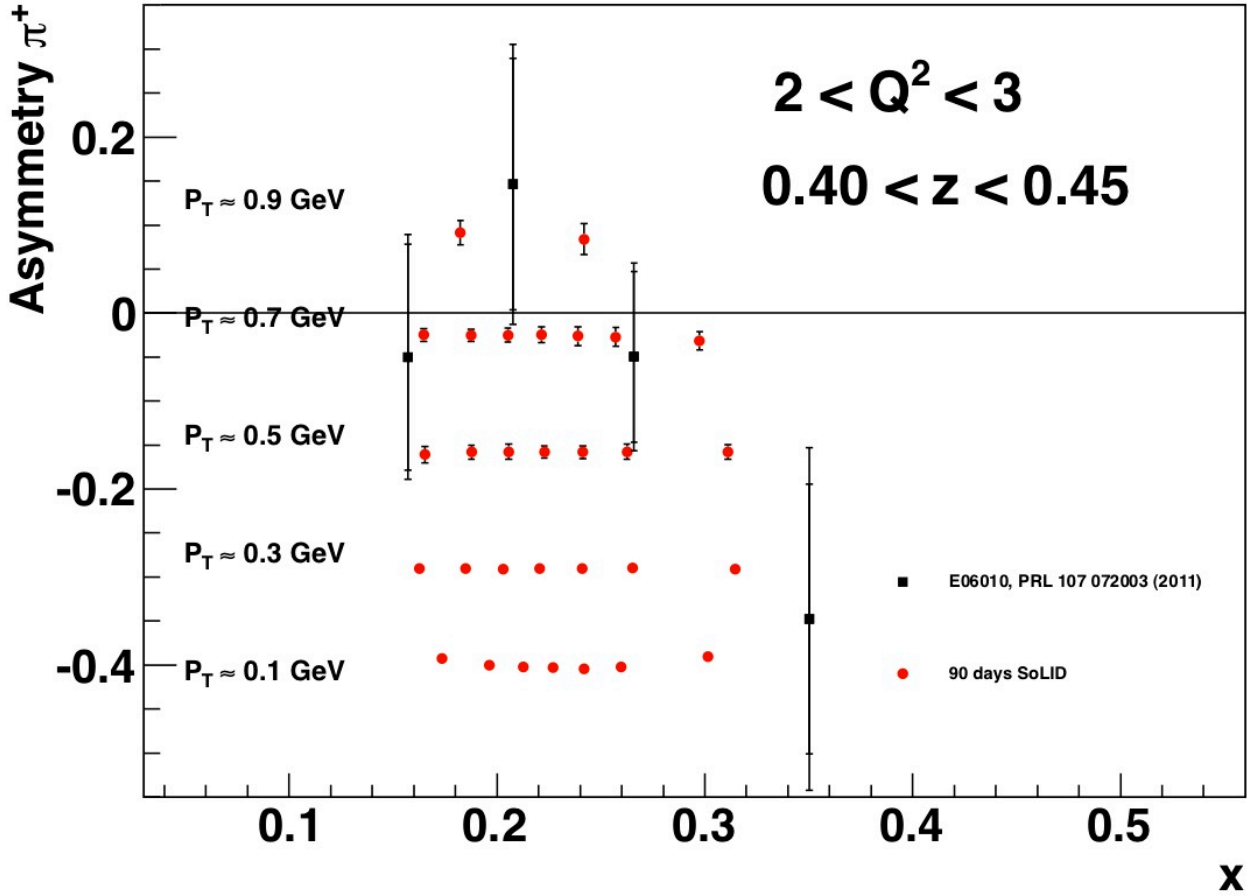
SoLID CLEO SIDIS



- GEMs for tracking
- Cherenkov and EM Calorimeter for electron PID
- Heavy Gas Cherenkov and MRPC (TOF) for pion PID

- CLEOII Magnet (official)
- pCDR just completed and submitted

Projected Data (E12-10-006)



Transversely Polarized ^{3}He

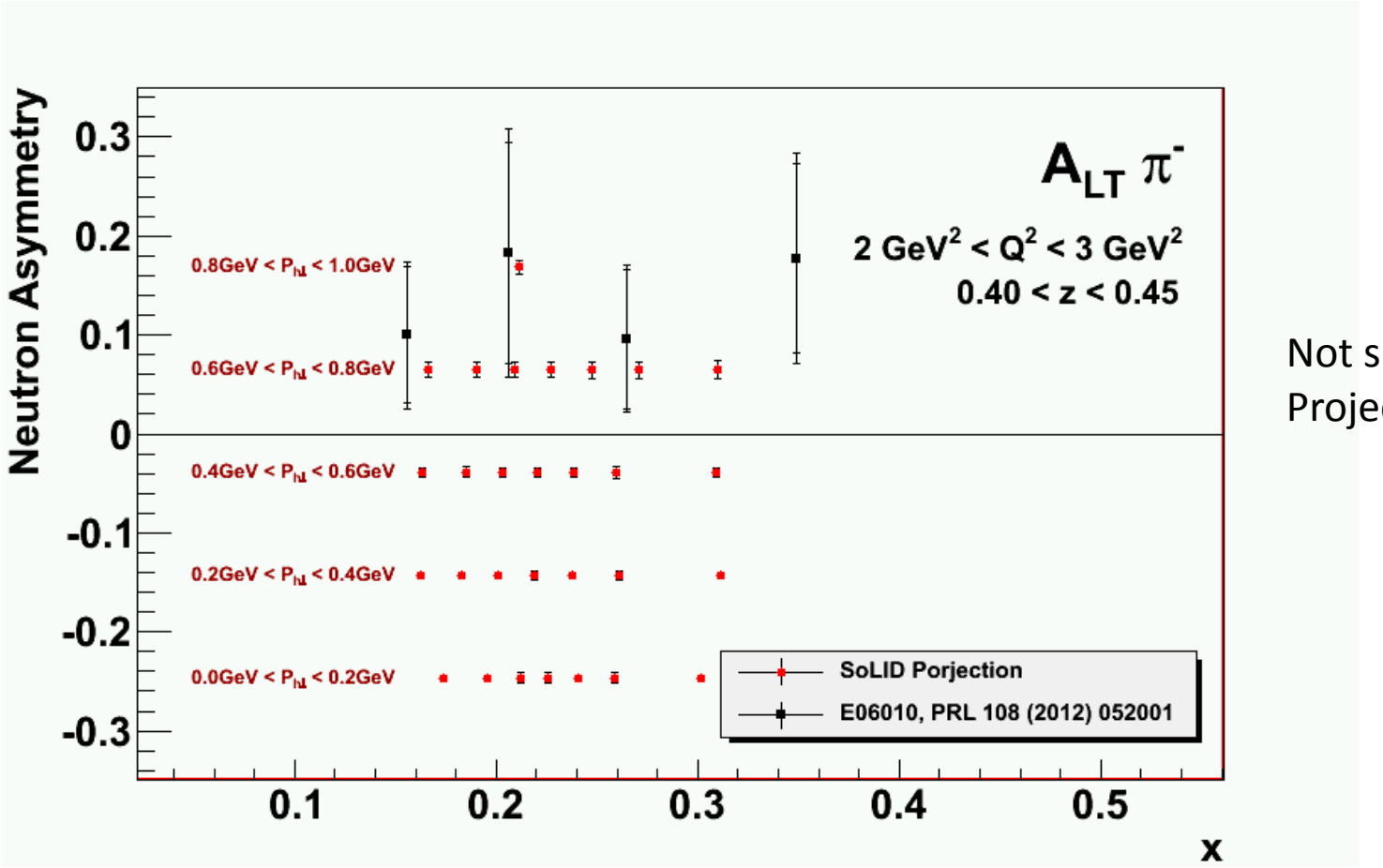
- Total 1400 bins in x, Q^2, P_T and z for 11/8.8 GeV beam.
- z ranges from 0.3 ~ 0.7, only one z and Q^2 bin of 11/8.8 GeV is shown here. π^+ projections are shown, similar to the π^- .

E12-10-006 Spokespersons: Chen, Gao (contact), Jiang, Qian and Peng (PAC A rating)

X. Qian et al in PRL 107, 072003

SoLID E12-11-007 Projection for A_{LT} (Partial)

- E12-11-007 and E12-10-006:
  Neutron A_{LT} Projection of one out of 48 Q^2-z bins for π^-



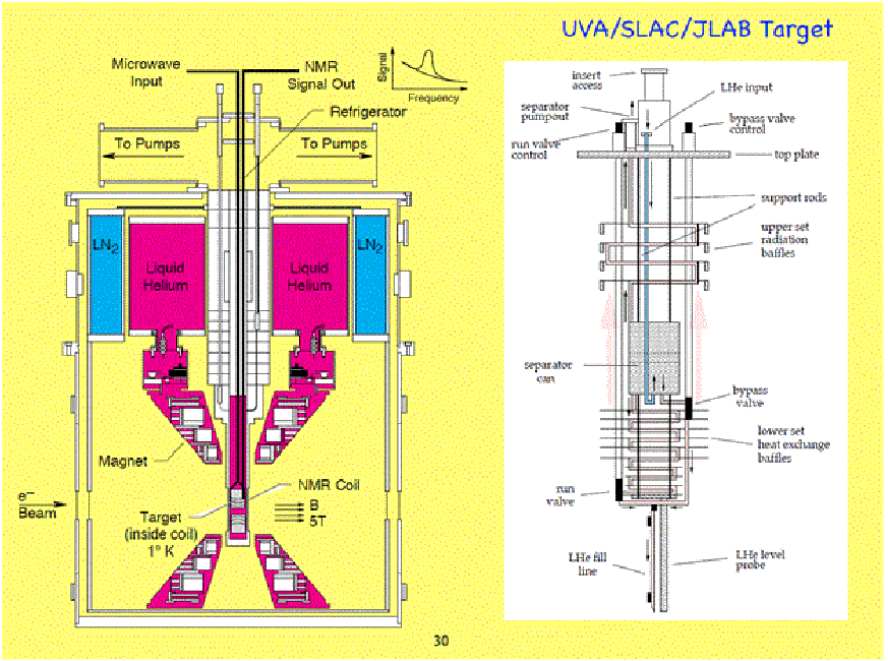
Not shown:
Projection for A_{UL}, A_{LL}

E12-11-007 spokespersons: J.P. Chen, J. Huang, Yi Qiang, W.B. Yan (USTC) (PAC A rating)
E06010 Results, J. Huang et al., PRL108, 052001 (2012)

Experiment E12-11-108:

Target Single Spin Asymmetry in SIDIS *(e, eπ±)* Reaction on a Transversely Polarized Proton Target and SoLID

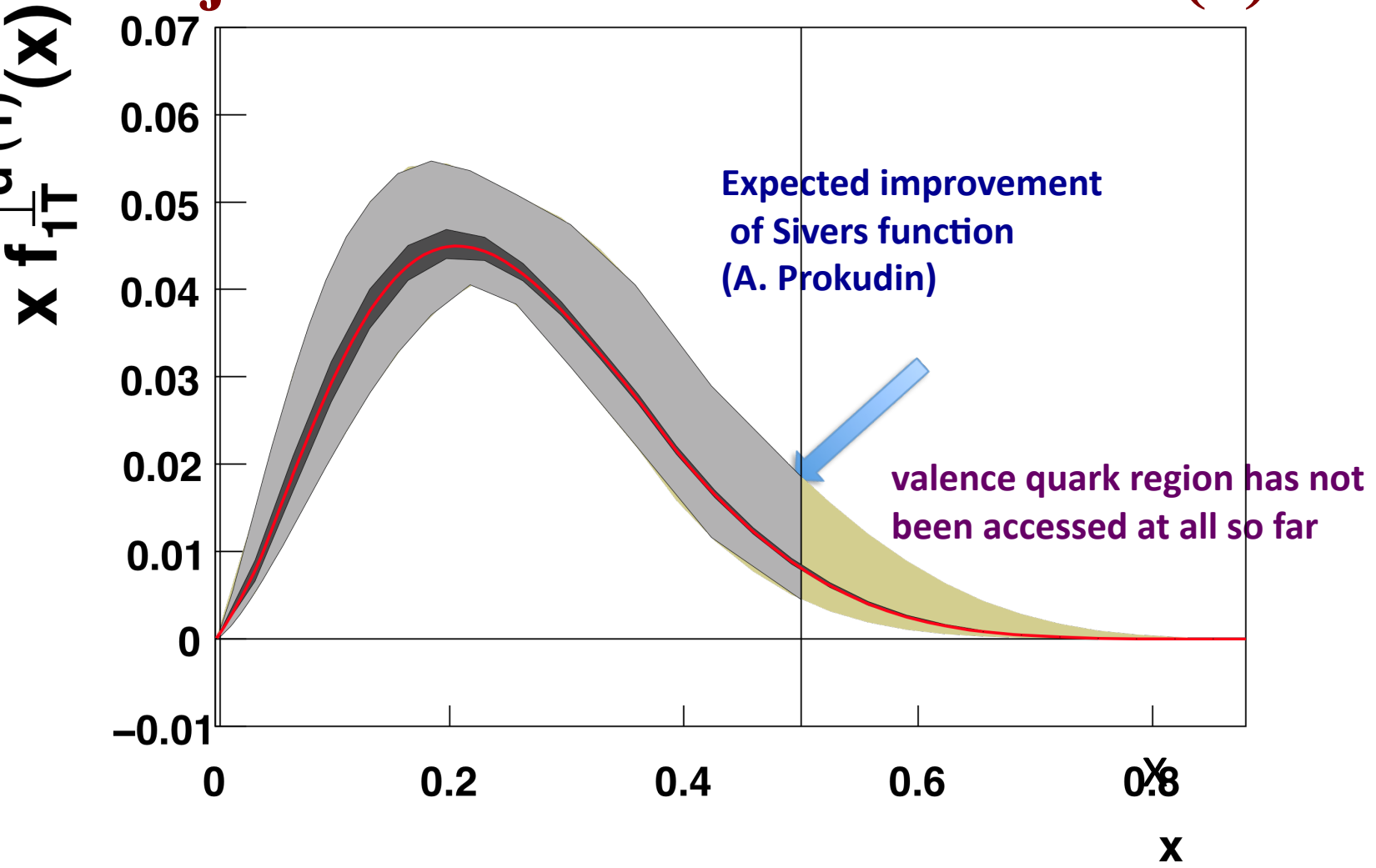
- Measure SSA in SIDIS using transversely polarized proton target
  - Use similar detector setup as that of two approved ^{3}He SoLID expts.
  - Use JLab/UVa polarized NH_3 target with upgraded design of the magnet
  - Target spin-flip every two hours with average in-beam polarization of 70%
  - Two Beam energies: 11 GeV and 8.8 GeV
  - Polarized luminosity with 100nA current: 10^{35} $cm^{-2}s^{-1}$
  - Beamline chicane to transport beam through 5T target magnetic field (already used for g2p expt.)



Spokespersons: K. Allada (Jlab), J. P. Chen (Jlab), Haiyan Gao (Contact), Xiaomei Li (CIAE), Z-E. Meziani (Temple)

PAC39: approved with A rating

Projected measurements in 1-D (x)



Assumption: We know the k_T dependence, Q^2 evolution of TMDs. Also knowledge on TMFF → project onto 1-D in x to illustrate the power of SoLID-^{3}He.

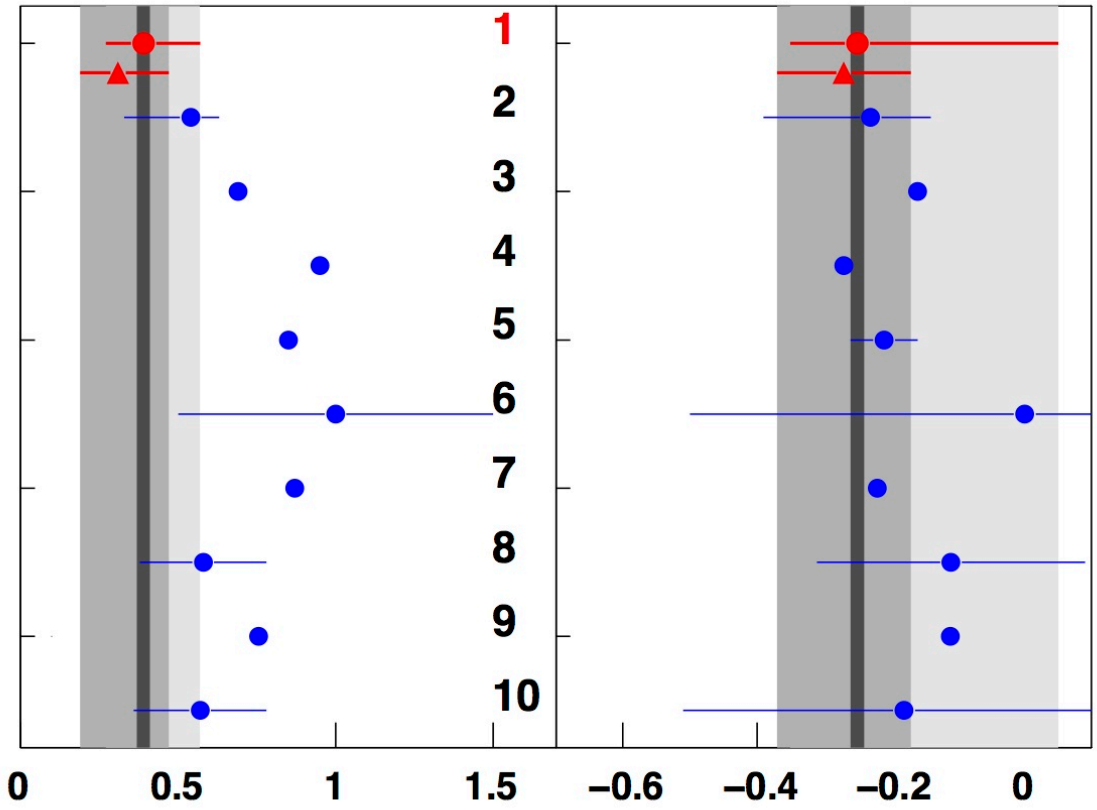
Jlab 12 GeV Program has major impact on Tensor Charge

1 – Anselmino et al (2013)
2 – Anselmino et al., Nucl. Phys. Proc. Suppl. (2009)
3 – Cloet, Bentz and Thomas, Phys. Lett. B (2008)
4 – Wakamatsu, Phys. Lett. B (2007)
5 – Gockeler et al., Phys. Lett. B (2005)
6 – He and Ji, Phys. Rev. D (1995)
7 – Pasquini et al, Phys. Rev. D (2007)
8 – Gamberg and Goldstein, Phys. Rev. Lett. (2001)
9 – Hecht, Roberts and Schmidt, Phys. Rev. C (2001)
10 – Bacchetta, Courtoy, Radici, arXiv:1212.3568

$$\delta q = \int_0^1 dx \, (h_1^q(x) - h_1^{\bar{q}}(x))$$

● $\delta u = 0.39^{+0.18}_{-0.12}$, $\delta d = -0.25^{+0.3}_{-0.1}$

▲ $\delta u = 0.31^{+0.16}_{-0.12}$, $\delta d = -0.27^{+0.1}_{-0.1}$



Statistics only

Thanks to A. Prokudin

Summary on SoLID TMD Program

- Unprecedented precision *4-d* mapping of SSA and DSA
  - Collins, Sivers, Pretzelosity and Worm-Gear
- Both polarized ^{3}He (n) and polarized proton with SoLID
- Three "A" rated experiments approved. One LOI on di-hadron.
- Study factorization with x and z-dependences
- Study P_T dependence
- Combining with the world data
  - extract transversity and fragmentation functions for both u and d quarks
  - determine tensor charge
  - study TMDs for both valence and sea quarks
  - learn quark orbital motion and quark orbital angular momentum
  - study Q^2 evolution
- Global efforts (experimentalists and theorists), global analysis
  - much better understanding of multi-d nucleon structure and QCD
- **Welcome new collaborators**

Supported in part by U.S. Department of Energy under contract number DE-FG02-03ER41231

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